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14. ABSTRACT

We have developd new techniques that enable characterization of ultrafast optical waveforms generated via spectral line-by-line pulse shaping under the Optical Arbitrary Waveform Generation (O-AWG) program. Our approaches simultaneously address a number of challenging requirements not met by existing waveform measurement methods, including high waveform complexity, high spectral resolution, and high sensitivity sufficient for single-frame waveform detection.

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Waveform Characterization for Spectral Line-by Line Pulse Shaping

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We have developd new techniques that enable characterization of ultrafast optical waveforms generated via spectral line-by-line pulse shaping under the Optical Arbitrary Waveform Generation (O-AWG) program. Our approaches simultaneously address a number of challenging requirements not met by existing waveform measurement methods, including high waveform complexity, high spectral resolution, and high sensitivity sufficient for single-frame waveform detection.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

"Optical Arbitrary Waveform Characterization via Dual-quadrature Spectral Interferometry," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, Optics Express 17, 25-33 (2009).

"Single Shot Amplitude and Phase Characterization of Optical Arbitrary Waveforms," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, Optics Express 17, 14434-14443 (2009).

“Fast Characterization of Dispersion and Dispersion Slope of Optical Fiber Links Using Spectral Interferometry,” V.R. Supradeepa, C.M. Long, D.E. Leaird, and A.M. Weiner, IEEE Photonics Technology Letters, Vol. 22, 155-157 (2010)

"Optical Arbitrary Waveform Characterization via Dual-quadrature Spectral Shearing Interferometry," H. Miao, D. E. Leaird, C. Langrock, M. M. Fejer, and A. M. Weiner, Optics Express 17, 3381-3389 (2009).

"Dual-comb Electric-field Cross-correlation Technique for Optical Arbitrary Waveform Characterization," F. Ferdous, D. E. Leaird, C. B. Huang, and A. M. Weiner, Optics Letters 34, 3875-3877 (2009).

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V.R. Supradeepa, D.E. Leaird, and A.M. Weiner, “Fourier pulse shaping with enhanced spectral control using a 2-D VIPA grating pulse shaper,” Conference on Lasers and Electro-optics, San Jose, CA, May 5-9, 2008.

"Single Measurement Retrieval of Amplitude and Phase of Wide Temporal Window Optical Waveforms using Dual-Quadrature Spectral Interferometry," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, IEEE Lasers & Electro-Optics Society Annual Meeting, Newport Beach, CA, November 9-13, 2008.

"Fast Amplitude and Phase Characterization of Optical Frequency Combs Propagation over 50 km of Optical Fiber Using Dual Quadrature Spectral Interferometry," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, Optical Fiber Communication Conference, San Diego, CA, March 22-27, 2009.

"Single Shot Characterization of Amplitude and Phase of Pulse-to-Pulse Switched Optical Arbitrary Waveforms from a 10 GHz Frequency Comb," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, Conference on Lasers and Electro-Optics, Baltimore, MD, June 1-5, 2009.

"Fast Characterization of Optical Arbitrary Waveforms from a 10 GHz Frequency Comb Using Dual-Quadrature Spectral Interferometry," V. R. Supradeepa, D. E. Leaird, and A. M. Weiner, Conference on Lasers and Electro-Optics, Baltimore, MD, June 1-5, 2009.

"Dual Comb Electric Field Cross-Correlation," F. Ferdous, C.-B. Huang, D. E. Leaird, and A. M. Weiner, Conference on Lasers and Electro-Optics, Baltimore, MD, June 1-5, 2009.

"Optical Frequency Comb Characterization via Spectral Shearing Interferometry in an A-PPLN Waveguide," H. Miao, C.-B. Huang, D. E. Leaird, C. Langrock, M. M. Fejer, and A. M. Weiner, IEEE Lasers & Electro-Optics Society Annual Meeting, Newport Beach, CA, November 9-13, 2008.

"Optical Frequency Comb Characterization-Self-Referenced Phase Retrieval via Spectral Shearing Interferometry in an A-PPLN Waveguide," H. Miao, C.-B. Huang, D. E. Learid, C. Langrock. M. M. Fejer and A. M. Weiner, Conference on Lasers and Electro-Optics, Baltimore, MD, June 1-5, 2009.

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(d) Manuscripts

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Patents Submitted

Patents Awarded

Graduate Students

NAME	PERCENT_SUPPORTED
Fahmida Ferdous	1.00
V.R. Supradeepa	0.75
Rui Wu	0.50
Houxun Miao	0.50
Robin Huang	0.50
FTE Equivalent:	**3.25**
Total Number:	**5**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Chris Long	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Andrew Weiner	0.20	Yes
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Under Graduate students supported

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Student Metrics

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Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Houxun Miao	
Robin Huang	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED	
Daniel Leaird	0.75	No
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Waveform Characterization for Spectral Line-by-Line Pulse Shaping

Table of contents

Problem statement

Optical arbitrary waveform generation efforts supported under the DARPA O-AWG program aim to achieve independent, line-by-line phase and amplitude control of 100 spectral lines within a 1 THz spectral band selected from an optical frequency comb with 10 GHz line spacing. In the time domain, the consequence of such frequency-domain encoding is generation of waveforms that may span a 100 ps time aperture, equal to the repetition period between pulses. Waveforms may have fine structure down to a few hundred femtoseconds and may be composed of ~100 temporal features (where adjacent features may have independent intensity and phase). Such waveforms are sketched schematically in Fig. 1 [1, 2]. Additionally, the OAWG program aims at rapid reprogramming of waveforms at time scales as fast as the pulse repetition period. Such advanced waveform generation capability is expected to enable new applications in high-speed lightwave communications, laser radar, radio-frequency photonics, and high-resolution, broadband optical spectroscopy.

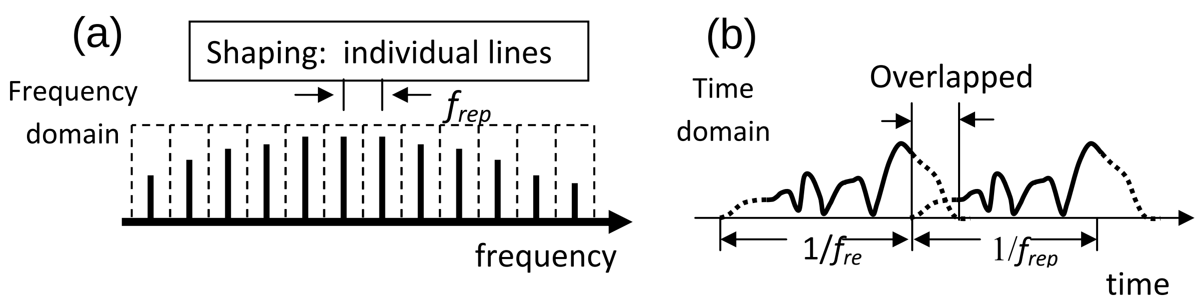


Fig. 1 (a) Line-by-line pulse shaping, in which phase and/or amplitude of adjacent comb lines is independently controlled. (b) Resulting optical arbitrary waveform generation. In the time domain, waveform contributions from adjacent input pulses necessarily overlap and coherently interfere. For the DARPA O-AWG program, the comb spacing and pulse repetition frequency satisfy f_{rep}*=10 GHz*.

Measurement of waveforms with such attributes is highly challenging and is well beyond the capabilities of established pulse characterization methods developed in the ultrafast optics community. In particular, existing pulse characterization methods have been developed for waveforms that are isolated in time (low duty factor). Characterization of waveforms with 100% duty factor, i.e., where adjacent waveform contributions overlap in time, has generally not been considered. Furthermore, these methods are generally applied to very short pulses (a few femtoseconds up to perhaps a few picoseconds). Consequently only coarse spectral resolution is required (approximately 100 GHz or below). Characterization of waveforms generated under O-AWG require much finer spectral resolution to cleanly resolve features encoded at 10 GHz line spacing. Finally, existing methods are conventionally applied to fields with smooth spectra, with gradual spectral phase and amplitude variations, and with relatively low complexity, e.g., time-bandwidth products below approximately 10. In contrast, OAWG will generate fields with discrete line spectra, with abrupt amplitude and/or phase changes from line to line, and with high complexity (time-bandwidth products up to approximately 100). In short, existing waveform characterization methods fail because they fail to provide simultaneous broad optical bandwidth and fine spectral resolution (equivalent to simultaneous fast time resolution and large time aperture).

In our project we developed several new techniques that address these shortcomings to enable intensity and phase characterization of O-AWG waveforms. In the following we describe results from three different waveform measurement techniques that we explored. The first two are wavelength-parallel measurement modalities with the potential to scale to single-frame waveform characterization, a particularly challenging requirement specified by DARPA to support characterization of rapid waveform reprogramming. (We actually pursued scaling to single-frame operation only in the first of these two techniques.) The third approach is a time-domain method suited primarily for characterization of static waveforms.

Method 1: Dual Quadrature Spectral Interferometry

Here we investigated a technique we call zero delay, dual quadrature spectral interferometry [3-5]. Spectral interferometry relies on the interference between an unshaped reference pulse and a shaped signal waveform of interest to yield the spectral phase of the signal (through analysis of the spectral fringes) [6, 7].

In conventional implementations (Fig. 2), to achieve unambiguous phase retrieval a delay greater than the temporal window of the measured signal waveform becomes necessary, and for long temporal window waveforms, this translates to excessively high spectral resolution requirements for the spectrometer. However, in dual quadrature spectral interferometry (Fig. 3a) two orthogonal polarization states are used to determine the in-phase and quadrature components of the interference between the unknown signal and a well characterized reference pulse simultaneously (preventing the need for delay fringes in the spectral domain). This allows for unambiguous phase retrieval without the need for a large delay and hence reduces the spectral resolution requirements. Also, being a linear technique, the measurement can work at low signal powers. It is important to note that this is not a self referencing technique and requires a well characterized reference pulse with respect to which the unknown signal pulse is measured. However once a well characterized reference pulse is available, a single measurement suffices for each waveform retrieval.

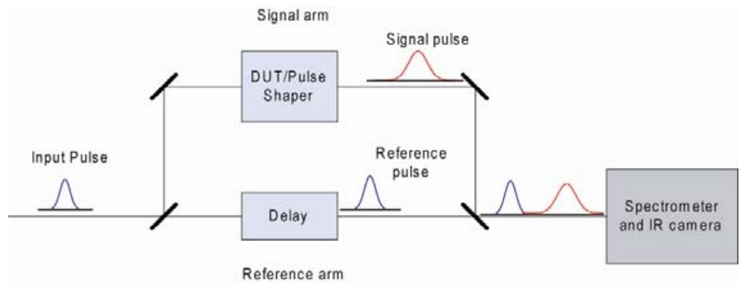


Fig. 2 Conventional approach to spectral interferometry. In order to unambiguously retrieve the spectral phase of a device under test, such as a pulse shaper, sufficient delay between pulses is required.

As an optical source our experiment (see Fig. 3a) utilizes a frequency comb generated via strong modulation of a continuous-wave laser. The signal to be measured is linearly polarized at a 45 deg angle while the reference is circularly polarized. These two beams are combined and followed by a home-made, high resolution spectrometer and an InGaAs IR CCD camera. The spectrometer simultaneously measures the interferograms in both polarizations (corresponding to the in-phase and quadrature terms) by mapping them to different physical locations on the camera. Representative dual interferograms recorded in our apparatus for frequency combs consisting of approximately thirty spectral lines are shown in Fig. 3b. The measured spectrometer crosstalk between two adjacent lines is approximately 5% and 8% respectively for the two adjacent channels. We retrieve waveform information from a single frame of camera data with 1.4 microsecond integration time, which defines the measurement time scale in the apparatus. For static waveform measurements, this fast acquisition time strongly reduces the effect of environmental fluctuations. We have used this apparatus to measurement a number of static OAWG waveforms [3] as well as to precisely characterize the dispersion of tens of kilometer lengths of optical fibers [5].

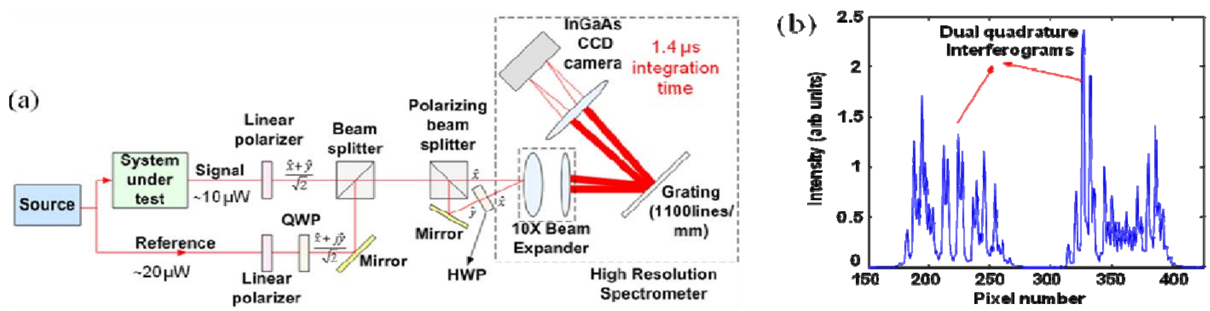


Fig. 3. Our zero-delay spectral interferometry scheme achieves simultaneous measurement of in-phase and quadrature interferograms in different polarizations, relaxing spectral resolution requirements. (a) experimental setup. (b) representative dual quadrature interferograms.

Here we focus our discussion on the challenging goal of single-frame waveform measurement, in which we characterize complex waveforms from only the photons in a single, 100-ps waveform frame [4]. Our experimental setup is sketched in Fig. 4a. A pair of modulators is used to blank a 100-line comb source to a single 100-ps waveform frame per 1.4 microsecond camera integration time. Care is taken to significantly exceed the 42-dB minimum extinction requirement needed based on the ratio of frame duration and integration period. The output is split into a reference and signal arm for spectral interferometry. The signal arm is again split and recombined with delay to generate a pulse pair. One of the arms within the signal arm passes through another integrated modulator, allowing one of the pulses in the pulse pair to be alternatively switched on and off. This results in a signal waveform that switches every frame from a single pulse to a pulse pair. Sampling oscilloscope traces of an individual pulse waveform and of a pulse pair waveform are shown in Fig. 4b,c respectively. This methodology allows us to perform critical tests of our spectral interferometry apparatus's ability to measure individual waveform frames.

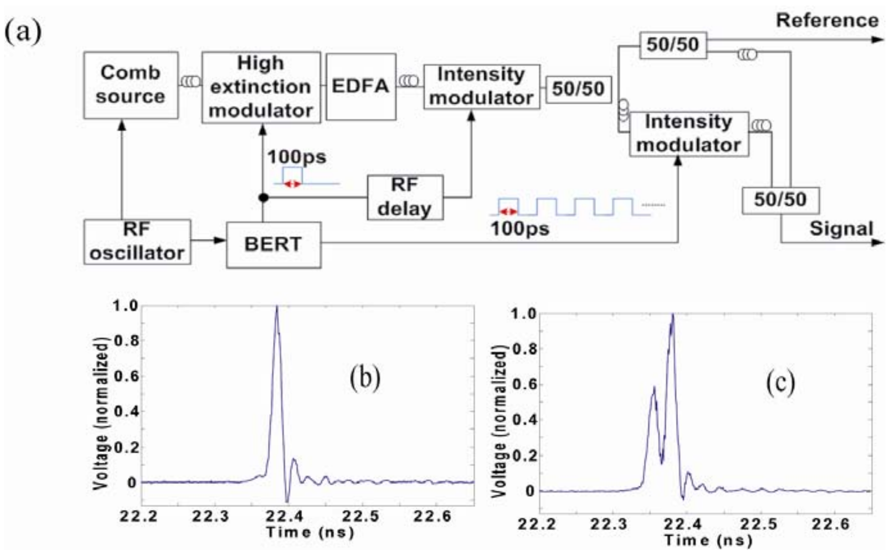


Fig. 4. Frame-by-frame waveform switching and characterization experiment. (a) set-up for generating switched waveform frames. (b,c) scope traces of (b) individual pulse waveform and (c) dual pulse waveform.

An example of the experimental results is shown in Fig. 5. The spectral amplitude and phase for each of 100 optical frequency components spanning a 1 THz bandwidth are shown in Figs. 5a and 5b for the single pulse waveform and for the pulse pair waveform, respectively. The spectral phase in Fig. 5a is relatively flat, as expected for a single, nearly bandwidth-limited pulse, while the spectral phase in Fig. 5b is quite irregular, due to expected spectral interference between the two pulses in the pulse pair. This confirms the ability to retrieve waveforms with complicated spectral phase. Figures 5c and 5d show the corresponding retrieved time domain intensity profiles of the single pulse and the pulse pair, respectively. For the pulse pair, the timing between the pulses and the relative pulse heights are in agreement with those recorded via oscilloscope, as shown in Fig. 4. This confirms the fidelity of our waveform retrieval process, even for single shot waveforms. However, the time resolution of our spectral interferometry approach (ca. 1 ps) is obviously much better than that provided by the fast sampling oscilloscope.

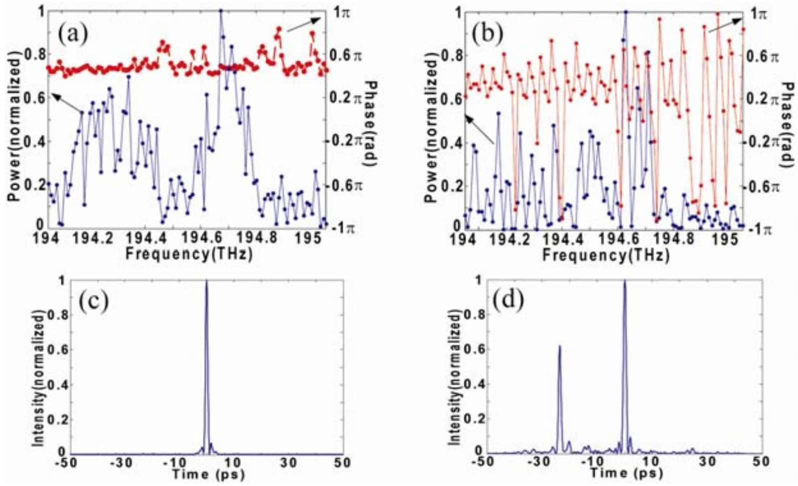


Fig. 5. Single-frame waveform characterization experimental results. (a,b) Retrieved spectral amplitude and phase and (c,d) corresponding time domain intensity profiles for (a,c) individual pulse waveform and (b,d) dual pulse waveform.

Method 2: Dual Quadrature Spectral Shearing Interferometry

The basic concept of spectral shearing interferometry, also known as SPIDER, is to generate two delayed versions of the waveform under test, shift one of them in frequency slightly with respect to the other, and look at the resulting spectral fringes [7, 8]. Spectral phase is extracted from analysis of the spectral fringe information. Compared to spectral interferometry as discussed above, this technique has the advantage of being self-referenced; no pre-characterized reference waveform is required. Although spectral shearing interferometry is widely applied in ultrafast optics, it has two key drawbacks for OAWG applications. In the following we summarize these and describe how we have modified the conventional scheme to support OAWG waveform characterization [9].

First, conventional SPIDER is most usually performed using a second harmonic generation (SHG) scheme to achieve the spectral shear. Due to the use of a nonlinear optical process, the efficiency is usually low. Therefore, the sensitivity is low and high optical power is needed. However, single frame waveform characterization under OAWG will require very high sensitivity. We have addressed this issue by generating the spectral shear via SHG in a quasi-phase matched nonlinear waveguide, which provides excellent nonlinear optical sensitivity. Although we have previously used such nonlinear waveguides in other pulse measurement schemes, the collinear geometry leads to a signal background that interferes with waveform retrieval. We have overcome this issue by introducing a new scheme whereby the sum frequency field (used for waveform retrieval) is shifted in wavelength from the background and can therefore be separated by optical filtering.

A second point is that the intrapulse delay introduced in the conventional technique increases demands on high spectral resolution to detect spectral fringes. In OAWG spectral resolution demands are already very high. Consequently we have introduced a new scheme which we call dual-quadrature spectral shearing interferometry, where the delay is set to zero. This relaxes the spectral resolution requirements to approximately the pulse repetition frequency and greatly facilitates practical implementation in a parameter range consistent with OAWG parameters.

Figure 6 shows an experimental block diagram. A continuous-wave laser is strongly phase modulated to form a comb of ~30 lines centered at 1542 nm and spaced by 10 GHz. A second continuous-wave laser is intensity modulated (5 GHz drive frequency, biased for carrier suppression) to form a pair of narrow lines spaced also by 10 GHz. These signals are combined and coupled into an aperiodically poled lithium niobate waveguide second harmonic generator. The sum frequency generation from this process is the superposition of two replicas of the input comb spectrum with a 10 GHz relative frequency shear. The resulting spectra are analyzed using a home-made spectrometer and electron multiplied camera.

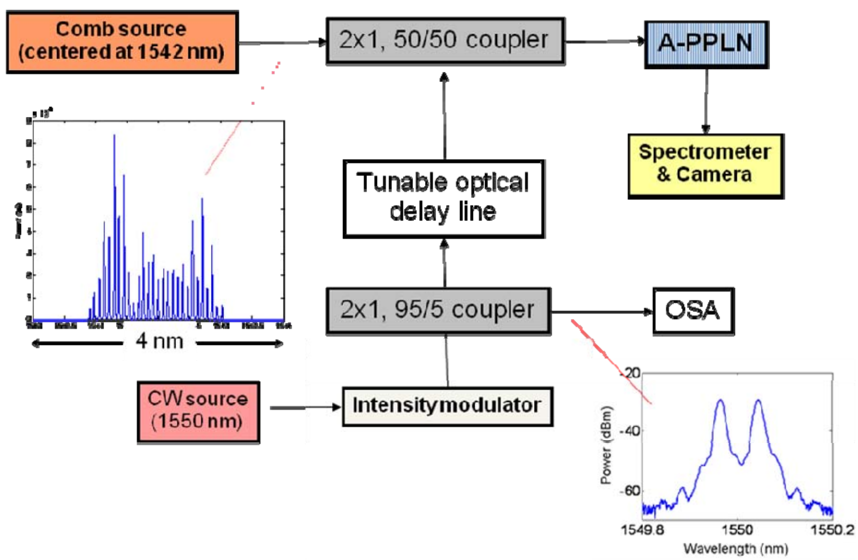


Fig. 6. Experimental approach for dual quadrature spectral shearing interferometry. An optical frequency comb is mixed with a pair of optical tones generated via modulation of a continuous-wave laser with variable delay. Analysis of the spectra generated via sum frequency generation in an aperiodically-poled lihtium niobate waveguide (A-PPLN) allows retrieval of frequency-dependent phase.

The desired spectral phase information is extracted from a series of four spectra taken at different relative delays between the input frequency comb signal and the line pair. Examples of the data are shown in slide 7. Here the sum frequency (SFG) signal of interest appears at the center of the various spectra. The unwanted self-terms from either the comb producing second harmonic (SHG) with the comb or the narrow line pair mixing with itself are spectrally displaced and can be separated. Note that the sum frequency spectrum varies according to delay. Analysis of this delay yields the spectral phase of the input comb.

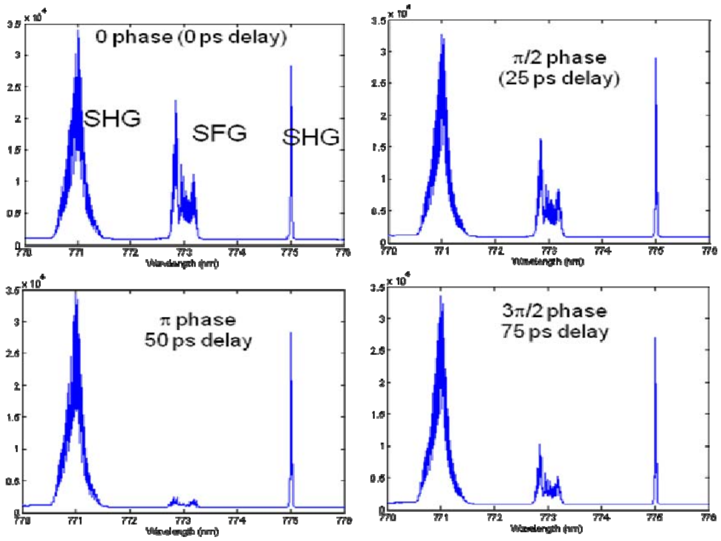


Fig. 7. Output spectra after second harmonic generation (SHG) and sum frequency generation (SFG) in an aperiodically-poled lihthum niobate waveguide (A-PPLN) for various RF phase shifts (various optical delays). The frequency-dependent phase of the input frequency comb is retrieved by analyzing the variation of the central (SFG) spectrum as a function of optical delay.

Figure 8 shows an example of pulse measurement in action. The comb spectrum directly after generation (power spectrum shown in Fig. 6), although spectrally broadened, is not yet a short pulse, since the spectral phases are not properly adjusted. This is shown both via the spectral phase data retrieved via our dual quadrature spectral shearing interferometry technique (Fig. 8a) and via the intensity autocorrelation (Fig. 8b), which is nearly constant over the full, 100 ps waveform period – indicative of a waveform whose temporal intensity profile is close to flat. As a next step, the results of the spectral phase measurement are programmed onto a high resolution optical pulse shaper, which imparts the opposite spectral phase onto the comb. This results in compression of the comb into a transformed-limited pulse train, consisting of pulses a few picoseconds long repeating at 10 GHz. This is verified by the intensity autocorrelation (Fig. 8c), which now shows clear pulse-like character and which is in excellent agreement with the theoretical autocorrelation calculated assuming perfectly flat spectral phase. This high quality pulse compression result validates both high accuracy phase retrieval and high accuracy pulse shaping.

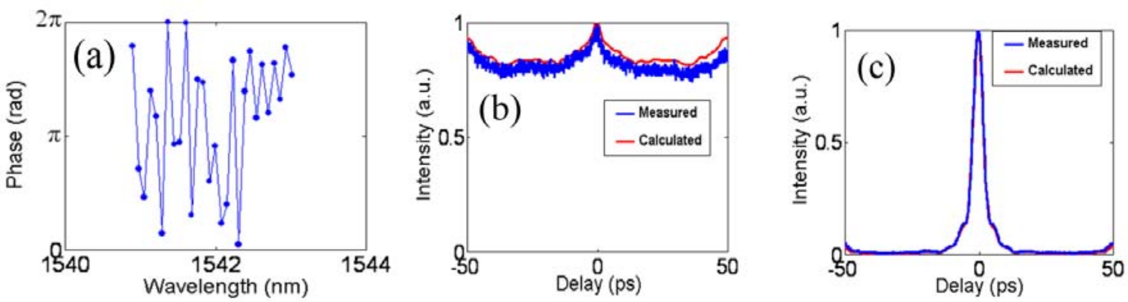
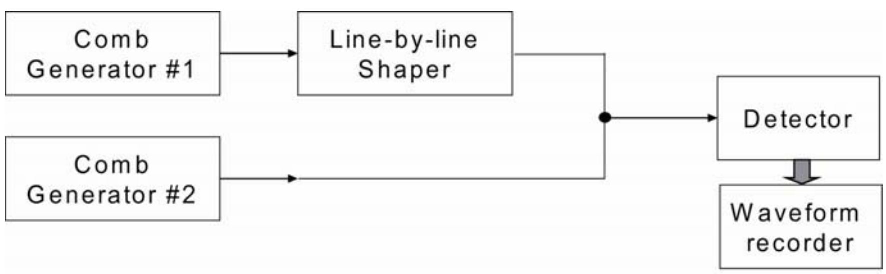


Fig. 8. (a) Retrieved spectral phase for comb shown in Fig. 6. (b) Intensity autocorrelation function measured for comb as generated. The trace is indicative of light with intensity that is close to flat in time. (c) Intensity autocorrelation for comb after compression based on applying inverse of retrieved spectral phase. The trace is indicative of high contrast pulses, validating accurate phase measurement

Method 3: Electric field cross-correlation

A final OAWG measurement method, technically known as electric field cross-correlation, is a repetitive sampling technique specially selected for application to measurement of static (repetitive) waveforms [7]. Its advantages include ease of implementation, direct rendering of waveforms in the time domain, rapid acquisition, and low optical power requirement. This technique, which may be considered a Fourier transform cousin of spectral interferometry, is not self-referenced, so in addition to the repetitive waveform requirement, there is the requirement to use of an already characterized reference pulse. As in all of the measurement techniques we have investigated, this method retrieves both amplitude and phase profiles of OAWG waveforms.

The schematic layout is shown in Fig. 9. As indicated in the equation, in electric field cross-correlation one measures an output signal consisting of a rapidly varying interference signal on top of a constant background determined by the pulse energies. The fringe term is the cross-correlation between the complex electric field amplitudes of a signal pulse $a_s(t)$ and a reference pulse $a_r(t)$. The fringes are recorded as a function of delay τ between signal and reference pulses. Provided that the reference pulse is a sufficiently short bandwidth-limited pulse, the measurement directly yields the signal pulse complex amplitude $a_s(t)$, which in our experiments is an OAWG waveform generated via a line-by-line pulse shaper.



$$\langle P_{out}(\tau)\rangle \sim U_r + U_s + \left[e^{j\omega_0\tau} \int dt\ a_s(t) a_r^*(t-\tau)\ +\ c.c. \right]$$

Fig. 9. Electric field cross-correlation approach for repetitive sampling of static OAWG waveforms. By using dual comb sources, relative delay is swept rapidly and automatically, eliminating the need for slow mechanical variable delay stages.

In conventional implementations of this technique, delay is scanned slowly using a mechanical stage. Here we report a novel implementation which exploits the unique properties of combs to rapidly sweep the delay without moving parts [10]. In particular, we generate two optical combs: a signal comb which goes through a line-by-line pulse shaper, and a reference comb which does not. The combs are intentionally detuned in repetition rate, which causes their relative delay to scan rapidly and automatically. The delay scans over one full waveform period at a frequency equal to the repetition rate detuning, which can be hundreds of KHz or even MHz. Furthermore, by using an acousto-optic modulator in the reference arm, we can controllably detune the optical frequencies of the two combs. This allows independent control of the rate at which optical phase sweeps (hence the rate at which interference fringes are generated) and the rate at which delay sweeps. This substantially eases memory requirements on the waveform recorder.

Figure 10 shows a simple example of our data. Here the measurement corresponds to an approximately bandwidth-limited signal pulse. The comb repetition frequencies are both nominally 10 GHz, but the reference comb repetition frequency is offset by 220 KHz. This causes the entire waveform spanning 100 ps to be scanned in 4.5 μs equivalent time. This very rapid sweep would be impossible using conventional mechanical delay stages. An expanded view clearly shows the individual interference fringes with 10 ns period. This corresponds to the 100 MHz shift of the optical frequency from our acousto-optic modulator. Overall there are about 450 fringes per waveform period. In contrast, a mechanical delay stage that scans phase and group delays at the same rate would result in about 20,000 fringes per waveform period. The reduced and controllable fringe count with our scheme substantially eases the requirements on the waveform recorder.

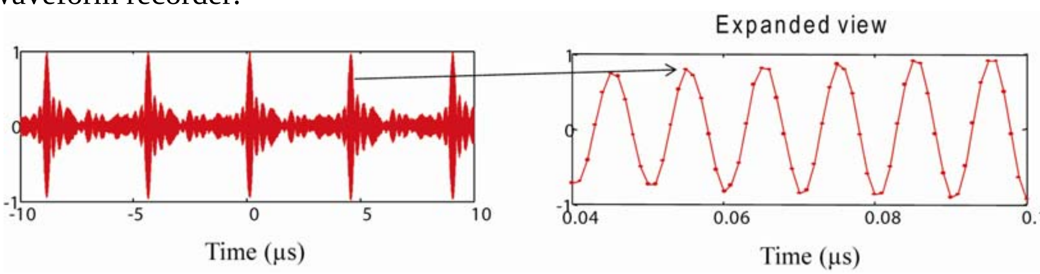


Fig. 10. Electric field cross-correlation traces of the complex electric field profile of bandwidth-limited signal pulses. The entire waveform period is scanned in 4.5 μs equivalent time. The expanded view shows that individual interference fringes occur in 10 ns equivalent time.

Finally, Fig. 11 shows examples of measurements for shaped waveforms. Figure 11a shows a measurement of a pulse doublet waveform obtained by programming a pulse shaper for an abrupt π phase shift onto half of the spectrum. Fourier transform analysis of this time domain trace yields the spectral phase (Fig. 11b), which is in close agreement with the programmed phase. A trace for a more complicated waveform is shown in Fig. 11c, corresponding to large cubic spectral phase. The retrieved spectral phase is once again in excellent agreement with the programmed phase.

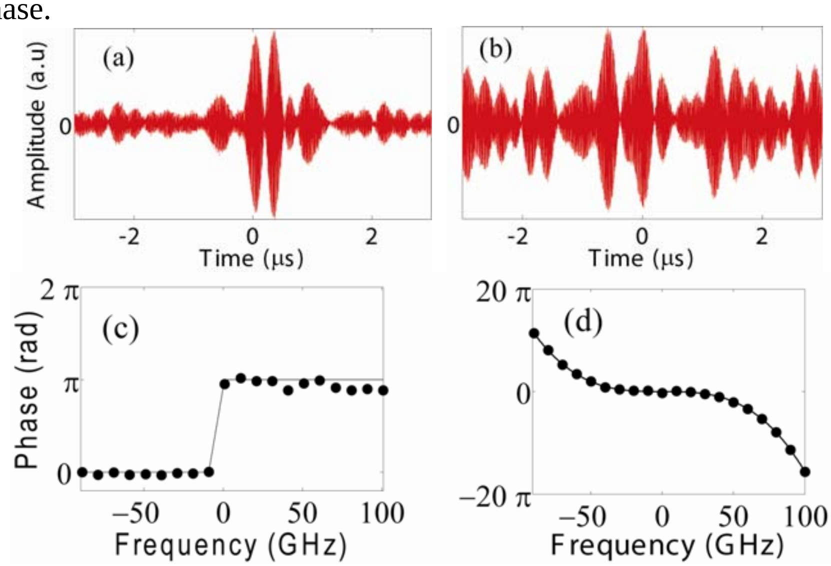


Fig. 11. (a,b) Electric field cross-correlation traces of shaped waveforms, generated by spectral phase shaping. (c,d) Corresponding retrieved spectral phase (dots) compared to phase programmed onto pulse shaper (lines). (a,c) Pulse doublet waveform corresponding to abrupt π phase shift spectrum. (b,d) Cubic spectral phase waveform.

Summary

In summary, we have investigated three different methods for measuring ultrafast optical arbitrary waveforms of interest for the DARPA OAWG program. All methods are capable of characterizing both amplitude and phase profiles of static OAWG waveforms, while a selected method has also been developed and demonstrated for measurement of dynamically varying waveforms on a single waveform frame (100 ps) basis.

References

[1] Z. Jiang, C. B. Huang, D. E. Leaird, and A. M. Weiner, "Optical arbitrary waveform processing of more than 100 spectral comb lines," *Nature Photonics*, vol. 1, pp. 463-467, Aug 2007.

[2] Z. Jiang, D. E. Leaird, and A. M. Weiner, "Line-by-line pulse shaping control for optical arbitrary waveform generation," *Optics Express*, vol. 13, pp. 10431-10439, Dec 2005.

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